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Spectral-Based Volume Sensor Prototype, Post-VS4 Test Series Algorithm Development

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14. ABSTRACT

A retrospective analysis was undertaken to better understand the performance trade-offs involved in reducing the sensor count in the Spectral-Based Volume Sensor Component Prototype developed as part of the Advance Volume Sensor Project. Using a portion of the Volume Sensor Test Series 4 (VS4) data, superior performance was retrospectively demonstrated for several potential new configurations than was originally observed during the live VS4 demonstration. Additionally, it was possible to maintain a large fraction of the performance while utilizing fewer sensor elements than the original SBVS Component Prototype configuration. On the basis of these analyses, the current recommendation for the SBVS Component in the All-in-One VSP being developed by Vibro-Meter, Inc. (VMI) currently under ONR sponsorship is either a UV/IR or a NIR/UV/IR configuration, depending on the data fusion systems' tolerance for increased probability of false alarms with increased probability of detection.

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ACRONYMS USED

Acronym	**Definition**
ADC	Advanced Damage Countermeasures Program
AiOVS	All-in-One Volume Sensor
B/W	Black and White
CCD	Charge Coupled Device
COTS	Commerical, Off-The-Shelf
CVN21	Future Aircraft Carrier, CVN 21. Formerly known as CVNX
CVNX	Carrier Vehicle, Nuclear Experimental
CVNX	CVN21 Fire Threat to Ordnance Test Series 2
DAQ	Data Acqusition (Hardware)
DataLogger	Data acqusition software written by NRL Code 6111
DC	Damage Control
DD(X)	DD(X), 21st Century Destroyer. The Navy's future multi-mission surface combatant. Also a series of shipboard testing conducted in 2005 on the ex-USS Shadwell
FA	False Alarm
FNC	Future Naval Capability, sponsored by ONR
FOV	Field Of View
FWHM	Full-Width, Half-Maximum, a measurement of the width of a spectral peak
IR	Infrared. In this document, IR refers to the mid-IR, around 4.3 mm.
LP	Longpass (filter), passes wavelengths greater than a cutoff wavelength
LWVD	Long Wavelength-response Video Detection
MV	Machine Vision
NIR	Near InfraRed
NRL	U.S. Naval Research Laboratory
OFD	Optical Flame Detector
ONR	Office of Naval Research
PC	Personal Computer
P_{corr}	Probabilty / Percentage of Correct Classification (# Correct / # Total)
PD	PhotoDiode
P_d	Probabilty / Percentage of Detection (# Correct Detections / Total of Sources)
P_{fa}	Probabilty / Percentage of False Alarm (# FAs / Total # of Sources)
SBVS	Spectral-Based Volume Sensor
SFA	Smoke and Fire Alert, a VIDS product of Fastcom Technology, S.A.
SigniFire	a VIDS product of axonX, LLC
UV	Ultraviolet
VID	Video Image Detection
VID(S)	Video Image Detection (System)
VS	Volume Sensor
VS1	Volume Sensor Test Series 1
VS2	Volume Sensor Test Series 2
VS3	Volume Sensor Test Series 3
VS4	Volume Sensor Test Series 3
VS5	Volume Sensor Test Series 3

EXECUTIVE SUMMARY

A retrospective analysis was undertaken to better understand the performance trade-offs involved in reducing the sensor count in the Spectral-Based Volume Sensor Component Prototype developed as part of the Advance Volume Sensor Project. Using a portion of the Volume Sensor Test Series 4 (VS4) data, superior performance was retrospectively demonstrated for several potential new configurations than was originally observed during the live VS4 demonstration. Additionally, it was possible to maintain a large fraction of the performance while utilizing fewer sensor elements than the original SBVS Component Prototype configuration.

The SBVS Component Prototype demonstrated as part of VS4 was comprised of sensor suites with five optical sensors (center wavelengths of 5900 Å (Na), 7665 Å (K), 10500 Å (NIR), solar-blind UV (UV), and 4.3 μm (IR)) and five EVENT algorithms (EVENT, PDSMOKE, FIRE, FIRE_FOV, and WELDING) generating alarm events for distribution to the overall Volume Sensor Prototype (VSP). A two-element configuration (UV/IR) shows improved performance over the as-tested VS4 configuration. Additionally, the probability of detection (P_d) for the WELDING EVENT was improved from 0.93 to 1.00 through optimization. The performance of the FIRE_FOV EVENT, which did not alarm for any of the selected test scenarios during the live demonstration, was further improved to yield 18 out of 60 detections.

Increasing the number of sensor elements in the configuration leads to increased P_d for the FIRE EVENT with increasing probability of false alarm (P_{fa}). The K/UV/IR combination offers little improvement in the FIRE Event P_d (0.82 vs. 0.80) while doubling the number of false alarms. This combination is not recommended. The NIR/UV/IR combination offers significant improvement in the FIRE EVENT P_d (0.95 vs. 0.80) while only adding 5 additional false alarms over the UV/IR combination. Especially interesting was that the FIRE EVENT false alarms generated were moved from the nuisance and welding test scenario classes to the cutting and grinding class. Hot work of these types are not typically conducted without significant preparation and system-wide notification in a shipboard environment and any DCA system would most likely be secured or operating in a special mode to handle this type of work. This reduces the potential severity of the generated false alarms. Using all four elements achieves an almost perfect P_d for the FIRE EVENT (0.98 or 0.97 vs. 0.80) while adding only 5-7 additional false alarms, depending on the threshold setting for the primary SBVS detection parameter, SumN. The performance statistics for the WELDING and FIRE_FOV EVENTs were unchanged in any of these configurations.

An example of potential inter-component data fusion is discussed for using the LWVD Component luminosity value in lieu of the NIR sensor element. One could potentially use the LWVD luminosity data stream in lieu of the NIR data stream to produce an effective 3-component SBVS system with only the UV and IR sensor elements. Or an effective 4-component system could be produced with only the K, UV, and IR sensor elements. This would require that the LWVD data stream exhibit similar sensitivity and dynamic range to that of the K photodiode. Data analysis along these lines is currently ongoing.

On the basis of these analyses, the current recommendation for the SBVS Component in the AiOVS being developed by Vibro-Meter, Inc. (VMI) currently under ONR sponsorship is either a UV/IR or a NIR/UV/IR configuration, depending on the data fusion systems' tolerance for increased P_{fa} with increased P_d.

Spectral-Based Volume Sensor Prototype, Post-VS4 Test Series Algorithm Development

1. INTRODUCTION

The Advanced Volume Sensor Project was one element of the Office of Naval Research's Future Naval Capabilities program, Advanced Damage Countermeasures. This program sought to develop and demonstrate improved damage control (DC) capabilities to help ensure that the recoverability performance goals for new ship programs, such as the CVN21 and the DD(X) families of ships, could be met with the specified manning levels and damage control systems. Using a multi-sensory approach, the Naval Research Laboratory (NRL) is developing new detection capabilities for DC in the shipboard environment. Conventional surveillance cameras, which are currently being incorporated into new ship designs, provide the basis for the Advanced Volume Sensor (VS) project. Video Image Detection (VID) is an emerging technology for the remote detection of events within the camera's field of view (FOV) by applying image analysis, or machine vision, techniques to the video image. Optical sensor systems sensitive to radiation outside the visible spectrum and acoustic sensors are also being developed in combination with the VID technologies to produce an overall sensor system that is able to provide a broad range of situational awareness for the sensor's entire field of view. The use of remote sensing techniques removes the constraint of typical smoke and fire detection systems that rely on diffusion of gases, particles, or heat to the detector. A Volume Sensor Prototype (VSP) was developed at NRL to provide an affordable, real-time, robust, and remote detection sensor system that provides detection and classification of damage control conditions such as fire, explosions, pipe ruptures, and compartment flooding. The VSP generates alarm notifications for action by the Damage Control Assistant and other available damage control systems based on the detected event. The VSP was successfully demonstrated in simulated shipboard conditions in several test series conducted on the ex-USS *Shadwell* in Mobile, AL.

The design goal of the Spectral-Based Volume Sensor (SBVS) Component is to detect fire, smoke, and other hazardous conditions using optical methods outside the visible region of the electromagnetic spectrum. The sensors developed within the SBVS Component are intended to be used in conjunction with and to augment the performance of the core VID technology of the VSP. The VID systems are generally better at identifying smoke than fire, so a primary goal of the SBVS Component is to provide better detection for flame and fire. An important constraint in the VS project is that the eventual system must be affordable with a target unit cost well below $1000. This precludes the use of more obvious solutions such as mid-infrared (IR) cameras because the per-unit price is too high (> $10,000 per unit). Two avenues have been pursued in parallel within the SBVS Component. One approach employs long wavelength video detection (LWVD), emphasizing the benefits of spatial resolution and near infrared imaging afforded by readily available, inexpensive video cameras. Descriptions and results of the LWVD system are provided in other reports [1,2] and in a patent [3]. The second avenue utilizes single-element detectors operating in several narrow spectral regions from the IR to the ultraviolet (UV) that correspond to the wavelengths of several peak flame emissions.

Initial laboratory and shipboard testing of the VSP in 2004 – 2005 was extremely successful. In 2008, the U.S. Congress allocated funds to Vibro-Meter, Inc. (VMI) through the Office of Naval Research to further the development of the VSP towards a commercially available product. The Volume Sensor Detection Suite prototype development effort is a joint effort between VMI and NRL to develop a commercially-viable VSP unit in a single package. The design and development of the All-In-One Volume Sensor (AiOVS) involves the evaluation of each sensor element in terms of added value to the

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performance of the AiOVS and the associated cost to incorporate that element. This report documents these analyses for the SBVS Component Prototype sensor elements and detection algorithms.

The organization of this report is as follows. Sections 2 and 3 briefly discuss SBVS Component Prototype hardware and event detection algorithms, respectively, as they have been tested in Volume Sensor Test Series 3 – 5 [4–6]. Section 4 provides a brief description of the VS4 Test Series, the data from which provided the basis of the analysis described in this report. Additional information can be found in Reference 5. Section 5 discusses the development of the All-In-One Volume Sensor (AiOVS) Prototype and the supporting additional analysis of the SBVS event algorithms associated with this effort. Sections 5 and 6 give the final, optimized results for the SBVS event algorithms based on the VS4 test data and recommendations for the development of the AiOVS Prototype. Section 7 contains the references cited in this document. Appendix A contains the complete definitions of the SBVS EVENT algorithms. Appendix B documents the finalized calibration factors for the 10 existing VSP units. Appendix C documents the parameter values for the various SBVS configurations discussed in this report.

2. SBVS COMPONENT PROTOTYPE HARDWARE

The SBVS Component Prototype is described in detail elsewhere [7] and is only discussed briefly here. Each SBVS Component Prototype sensor suite is composed of two units, the VIS/IR unit and the UV unit. A typical installation of a SBVS Component Prototype sensor suite for the VS5 Test Series is shown in Figure 2-1. The VIS/IR unit contains three Si photodiodes (PDs) with interference filters centered at 5900 (Na), 7665 (K), and 10500 (NIR) Å (bottom unit, starting from the right in Figure 2-1), each with a full-width, half-maximum (FWHM) band width of ~10 nm. Each unit has a mid-IR (IR) detector installed with a central operating wavelength of 4.3 μm (bottom unit, left-hand element). Several of the units have a second IR detector with a central operating wavelength of 2.7 μm (2.7 μm + 4.3 μm for sensor suite #53). The data from the second IR detector are not currently used by any algorithm and, where present, are recorded only for future research and development. The UV units (upper unit in Figure 2-1) are designed around a standard UV-only OFD (Vibrometer, Inc.). The OmniGuard 860 Optical Flame Detector (Vibrometer, Inc.) used in the original SBVS Testbed contained the same UV sensor unit. As of present, nine pairs of VIS/IR and UV units and a single AiOVS mock-up unit have been fabricated. As outlined in a previous report [8], a distributed-architecture data acquisition system was designed and implemented for the SBVS Component Prototype of the VS Prototype using the FieldPoint line (National Instruments) of data acquisition equipment.

Figure 2-1 – Typical installation of the SBVS Component Prototype as tested in VS5 Test Series. The UV unit is positioned above the VIS/IR unit. See the text for a description of the individual elements.

3. SBVS COMPONENT PROTOTYPE ALGORITHMS

Event detection algorithms for five events were implemented for the real-time use of the SBVS Component Prototype. The development of these algorithms is presented in Reference 9. These events are: EVENT, PDSMOKE, FIRE, FIRE_FOV, and WELDING. The EVENT was conceived as a generic trigger, indicating that some, currently unclassifiable event is occurring in the FOV of the sensor. The PDSMOKE event makes use of long-time-scale deviations observed in the 5900 Å channel data that were not correlated with flaming events to detect and classify smoke within the sensor FOV. The algorithms for FIRE and FIRE_FOV detection compare the measured channel data "spectrum," or the pattern of channel values for the five sensors to an empirically determined spectrum for a fully involved flaming fire in the sensor FOV for the FIRE_FOV event, or to a more relaxed spectrum for the FIRE event. An algorithm for the positive detection of one type of nuisance, arc welding was also included. To reduce the algorithm sensitivity to transient signals, a persistence criterion of five seconds was applied to the algorithm outputs (25 seconds for the PDSMOKE algorithm). All raw channel data were recorded locally on one of the SBVS Component data acquisition computers. Baseline-subtracted and normalized sensor channel data and algorithm outputs were forwarded to the VSP Fusion Machines (FM) using the VSCS communications protocol. Based on analysis of the VS3 test series data, two changes were made to the SBVS Component Prototype algorithms of Reference 9 to improve performance. First, the PDSMOKE algorithm was modified to correctly allow for both positive and negative deviations in the 5900 Å channel data. Also, individual calibrations were implemented for the SBVS hardware in each sensor suite to allow for unit-to-unit variations.

Appendix A gives a complete listing of the SBVS EVENT parameters and the EVENT algorithm descriptions. See Reference 9 for further details. The FIRE EVENT algorithm definition is given below.

```
Fire:       IF (Sum_N >= 0.0825) and (7665A >= 0.015) and
            (10500A >= 0.015) and (RefIR/UV >= 1) Then
                  FIRE = TRUE
            Else
                  FIRE = FALSE.
```

As part of the original SBVS algorithm development, a principal component analysis (PCA) was conducted on all of the data channels in the SBVS TestBed. A single principal component was identified, labeled SumN, which is defined as the sum of the scaled signals from the four principal sensor elements in the SBVS Component Prototype: the K and NIR PDs, the UV, and the IR sensors. Procedurally, SumN is defined as:

```
SumN = 7665A + 10500A + (0.1 * RefIR) + UV
```

In Reference 9, the definition of SumN included the 5900 Å (Na) PD data values. In subsequent algorithm iterations, the Na PD data was completely compartmentalized into the PDSMOKE EVENT algorithm and not used in either the determination of SumN or in the FIRE, FIRE_FOV, or WELDING EVENT definitions. From the definition of the FIRE EVENT, several thresholds are apparent and these are the parameters that will be varied in this analysis for each potential configuration of the new AiOVS.

4. VOLUME SENSOR 4 TEST SERIES

4.1. GENERAL INFORMATION

The objective of the VS4 test series [5] was to evaluate prototype sensor suites and alarm algorithms onboard the ex-USS *Shadwell* in preparation for demonstrating VSP systems in FY05. In particular, the tests were designed to assess the developmental progress of the VSP system since the Test Series 3 evaluation in July 2004 and to expand the database of scenarios and sensor measurements. These tests were conducted October 18-29, 2004.

Full-scale experiments were conducted aboard the ex-USS *Shadwell* in Mobile, AL [10]. This test series consisted of small fires, adjacent space fires, various nuisance sources, and pipe ruptures that challenged the detection systems. Two VSPs comprised of three prototype sensor suites, one of the evaluated VIDS, and containing newly-developed data fusion algorithms were installed for the test series. The performance of the VSPs and the VID systems were compared to the response of commercial off the shelf (COTS) smoke detection technologies.

4.2. SELECTED TEST SCENARIOS

The tests were conducted in and around the mock magazine on the 3rd deck of the ex-USS *Shadwell*. The test matrix for the VS4 Test Series consisted of one hundred (100) test scenarios. A variety of fire, nuisance, pipe rupture, and gas release sources were created to expose the VSPs and spot-type detectors to a range of potential shipboard scenarios. Small fires were used to challenge the detection systems and provide performance results for early detection. A number of the nuisance sources involved people moving about the space. Pipe ruptures were simulated with a range of flow rates and leakage areas to challenge the VSP. Further information on the VS4 test matrix can be found in Reference 5. For the purposes of SBVS algorithm development, 52 exemplar VS4 test scenarios were selected which represented unique, single events relevant to the SBVS. There were three SBVS sensor suites installed in the test space with differing FOVs in the compartment, for a total of 156 data sets. The test scenarios were broken down into four classes: 20 flaming, 5 welding tests, 8 cutting and grinding, and 19 nuisance test scenarios. The specific tests are identified in Table 4-1 – Table 4-4.

Table 4-1 – Test Series VS4 Selected Flaming Test Scenarios

Test	SBVS Root Filename	Test Description
VS4-001	Oct182004_133159	Flaming Cardboard Boxes with Polystyrene pellets
VS4-006	Oct192004_093503	Flaming Trash Can
VS4-009	Oct192004_130003	Flaming Shipping Supplies
VS4-015	Oct192004_160403	Flaming IPA Spill Fire / Trash bag
VS4-018	Oct202004_102359	Flaming Cardboard Boxes with Polystyrene pellets
VS4-022	Oct202004_131459	Flaming Trash Can
VS4-026	Oct202004_163000	Flaming Cardboard Boxes with Polystyrene pellets
VS4-027	Oct212004_082558	Flaming Shipping Supplies
VS4-032	Oct212004_112458	Flaming IPA Spill Fire / Trash Bag
VS4-038	Oct212004_154958	Flaming Trash Can
VS4-043	Oct222004_093358	Flaming Shipping Supplies
VS4-044	Oct222004_103758	Flaming IPA Spill Fire / Trash Bag
VS4-050	Oct252004_084500	Flaming Shipping Supplies
VS4-053	Oct252004_100600	Flaming IPA Spill Fire / Trash Bag
VS4-058	Oct252004_124359	Flaming Cardboard Boxes with Polystyrene pellets
VS4-068	Oct262004_100059	Flaming IPA Spill Fire / Trash Bag
VS4-070	Oct262004_120759	Flaming Cardboard Boxes with Polystyrene pellets
VS4-082	Oct272004_092458	Flaming Cardboard Boxes with Polystyrene pellets
VS4-091	Oct272004_160158	Hot metal surface - IPA spill under slanted cab door
VS4-096	Oct282004_104258	Flaming trash can - Camera 4 tilted up

Table 4-2 – Test Series VS4 Selected Welding Test Scenarios

Test	SBVS Root Filename	Test Description
VS4-002	Oct182004_143359	Welding
VS4-008	Oct192004_121902	Welding (140 A)
VS4-083	Oct272004_100558	Welding
VS4-090	Oct272004_152358	Welding preceded by no, normal, and high ventilation
VS4-092	Oct272004_163357	TIG welding stainless steel

Table 4-3 – Test Series VS4 Selected Cutting and Grind Test Scenarios

Test	SBVS Root Filename	Test Description
VS4-005	Oct192004_084001	Torch Cut Steel
VS4-014	Oct192004_153802	Grinding Painted Steel
VS4-025	Oct202004_155331	Torch Cut Steel
VS4-035	Oct212004_135258	Grinding Painted Steel
VS4-056	Oct252004_111359	Grinding Painted Steel
VS4-077	Oct262004_150959	Grinding Painted Steel
VS4-085	Oct272004_121658	Grinding Painted Steel
VS4-089	Oct272004_145858	Torch Cut Steel

Table 4-4 – Test Series VS4 Selected Nuisance Test Scenarios

Test	SBVS Root Filename	Test Description
VS4-004	Oct182004_163659	VHF Radio / People working
VS4-010	Oct192004_134803	Waving materials
VS4-012	Oct192004_150203	Spilling Metal Bolts
VS4-013	Oct192004_151903	AM/FM Radio / Cassette player
VS4-016	Oct202004_083159	Engine Exhaust
VS4-019	Oct202004_110859	TV / People working in space
VS4-020	Oct202004_113659	TV with video
VS4-024	Oct202004_151700	Normal Toasting
VS4-029	Oct212004_100257	People working in space - clean up pipe rupture
VS4-034	Oct212004_132657	Heat gun / space heater / fan
VS4-052	Oct252004_095000	People working in space - clean up pipe rupture
VS4-055	Oct252004_105300	People working in space - clean up pipe rupture
VS4-064	Oct262004_083159	Engine Exhaust
VS4-066	Oct262004_092359	Aerosol
VS4-067	Oct262004_094359	Flash Photography
VS4-081	Oct272004_091058	Flash Photography with four people
VS4-098	Oct282004_124158	Space heater
VS4-099	Oct282004_130058	Toaster
VS4-100	Oct282004_131258	Space heater

5. SBVS ALGORITHM DEVELOPMENT

A final demonstration was planned for the Advanced Damage Countermeasures FNC in the Fall of 2005. The post-VS5 Volume Sensor Prototypes were to be included in this demonstration as an integrated part of an overall damage control system. While the VSPs had previously demonstrated significant added performance for detection and classification of damage control events, the prototype nature of the system did not allow one to easily envision the potential final products. An example of a complete VSP sensor suite installation is shown in Figure 5-1. NRL and VMI determined that it would be advantageous to have available a mock-up of what a production unit might look like, the more functional the better. This was also considered an opportunity to review the added value of each of the 5 remaining SBVS sensor elements and determine which ones were required to maintain performance. Due to the events surrounding Hurricane Katrina, the final demonstration was never held, but the AiOVS mock-up has been useful at various meetings and presentations as a talking point that can be held in one's hand. During a magazine test conducted in the Winter of 2008, as part of a new program, the VSPs and the AiOVS mock-up were installed for demonstration.

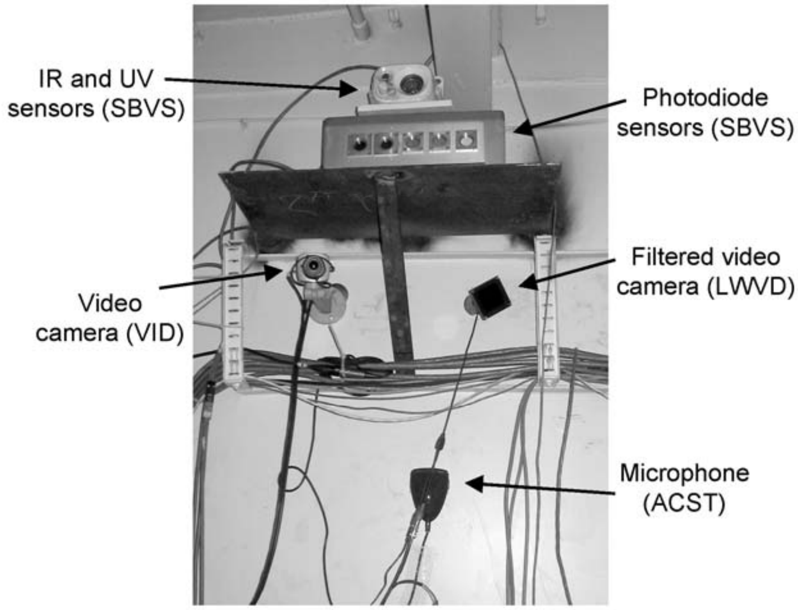

Figure 5-1 – Volume Sensor Prototype Sensor Suite including VIDS, ACST, SBVS, and LWVD components.

5.1. ALL-IN-ONE PROTOTYPE

Based on preliminary evaluations (See Section 5.3.2 for further discussion), the AiOVS mockup shown in Figure 5-2 was constructed by VMI with two Si-CCD cameras (one color CCTV and one LWVD filtered B&W camera), the IR and UV sensors from the SBVS Component, and a microphone.

Figure 5-2 – All-in-One Volume Sensor mock-up constructed by VMI in 2005.

As part of ONR's Volume Sensor Detection Suite prototype development effort, the preliminary analyses that lead to the down-selection of the SBVS sensor components to only the IR and UV sensors was to be reviewed in greater detail. The remainder of this report will discuss these analyses.

5.2. DEVELOPMENT TOOLING

To partially automate the data analysis process, a software package, SBVS_Replay, was developed in-house at NRL to reprocess previously collected data files while allowing sensor calibration and algorithm threshold parameters to be varied. A screenshot of the program operating is shown in Figure 5-3. The operator can select one or more archival data files from Test Series VS3, VS4, and VS5 / DD(X). The label DD(X) refers to several test series conducted in 2005 for which the VSPs were run in the VS5 configuration along side the main demonstration. The tool is currently limited to only being able to process data from one test series at a time because the data file formats were updated prior to each of these test series. The program automatically detects the test series type from the file format and loads the appropriate calibration factors for each sensor unit. For VS3 and VS4 data files, the calibration factors are displayed in the upper left of the screen and are user-editable from within the program. Due to the large number of parameters for VS5 / DD(X), the calibration factors are stored in the system registry and can be viewed / updated there. The operator is then able to select which of the five sensor elements will be considered in the reprocessing (lower left of screen). The right-hand side of the screen is devoted to the algorithm thresholds and parameters. The persistence in seconds, or duration of an event, required to trigger an event are displayed in the middle left of the screen. Once the operator has configured the run as desired, the selected data files are reprocessed using the new parameters and a composite output file is generated for all files processed. This program allows the operator to systematically vary a parameter and observe the results easily.

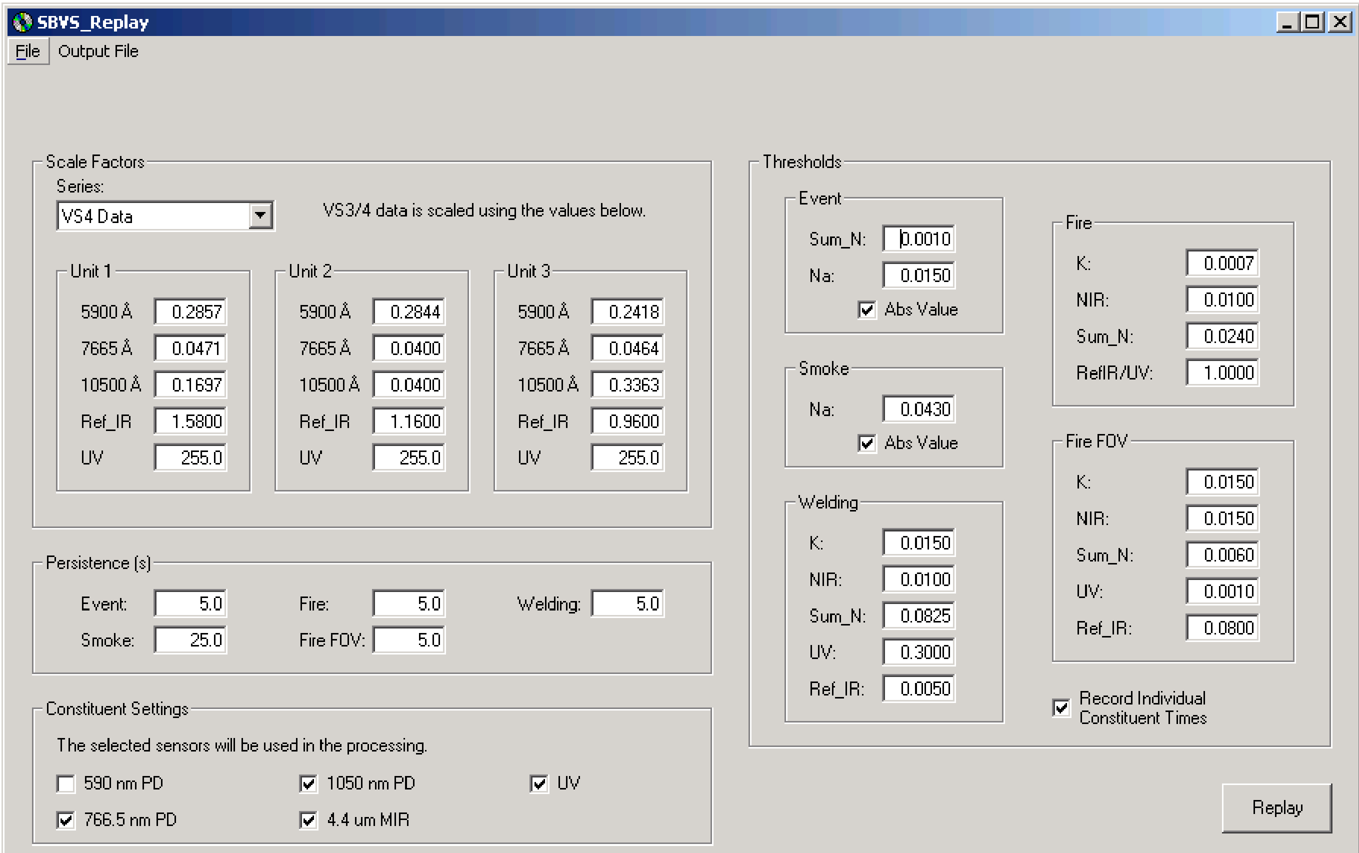

Figure 5-3 – Screenshot of the SBVS_Replay tool.

5.3. ANALYSIS RESULTS

In support of ONR’s Volume Sensor Detection Suite prototype development effort, a detailed examination of the relative added value of each sensor component was evaluated with the goal of reducing the SBVS sensor count from the current 5 to 2 or 3 sensors in a rigorous and defensible manner while retaining or even improving performance. The original SBVS algorithms were developed from the SBVS Testbed sensor data collected during the VS2 Test Series [9]. Given the continued evolution of the SBVS Component Prototype since that time, a fresh look was warranted. A subset of the VS4 Test Series data archive was selected for analysis as described in Section 4. One caveat that should be kept in mind is that SBVS calibration procedures for the individual units were under development throughout this period. All new analyses discussed in this document use the final VS5 calibration values as listed in Appendix B. The VS5 recommended algorithm formulations were used as an initial starting point as well.

5.3.1. VS4 TEST SERIES AS-TESTED RESULTS

The ‘As-Tested’ results for the SBVS Component Prototype for the 52 selected test cases are summarized in Table 5-1 and shown in Figure 5-4. Using a color-coding scheme which will be used for the remainder of this discussion, results which are considered beneficial to performance are color-coded green and results which are considered detrimental to performance are color-coded red. The numbers in the lower right of each cell represent the number of test scenarios (tests * # of sensor suites (3)). The numbers in the upper left of each cell represent the number of EVENT alarms found by the reprocessing with the SBVS_Replay software. As tested, the SBVS Component Prototype detected 41 of the 60 flaming test scenarios, all via the FIRE EVENT. The WELDING EVENT detected 14 of the 15 welding test scenarios. The FIRE_FOV EVENT failed to alarm for any test scenario, the FIRE EVENT false alarmed for 7, and the WELDING EVENT false alarmed for 5 of the 24 cutting and grinding test scenarios. The PDSMOKE EVENT alarmed as given in the Table.

Table 5-1 – SBVS Component Prototype ‘As-Tested’ algorithm results

	FIRE	PDSMOKE	FIRE_FOV	WELDING
Flaming	41 / 60	25 / 60	0 / 60	0 / 60
Welding	0 / 15	8 / 15	0 / 15	14 / 15
Cutting and Grinding	7 / 24	0 / 24	0 / 24	5 / 24
Nuisances	0 / 57	5 / 57	0 / 57	0 / 57

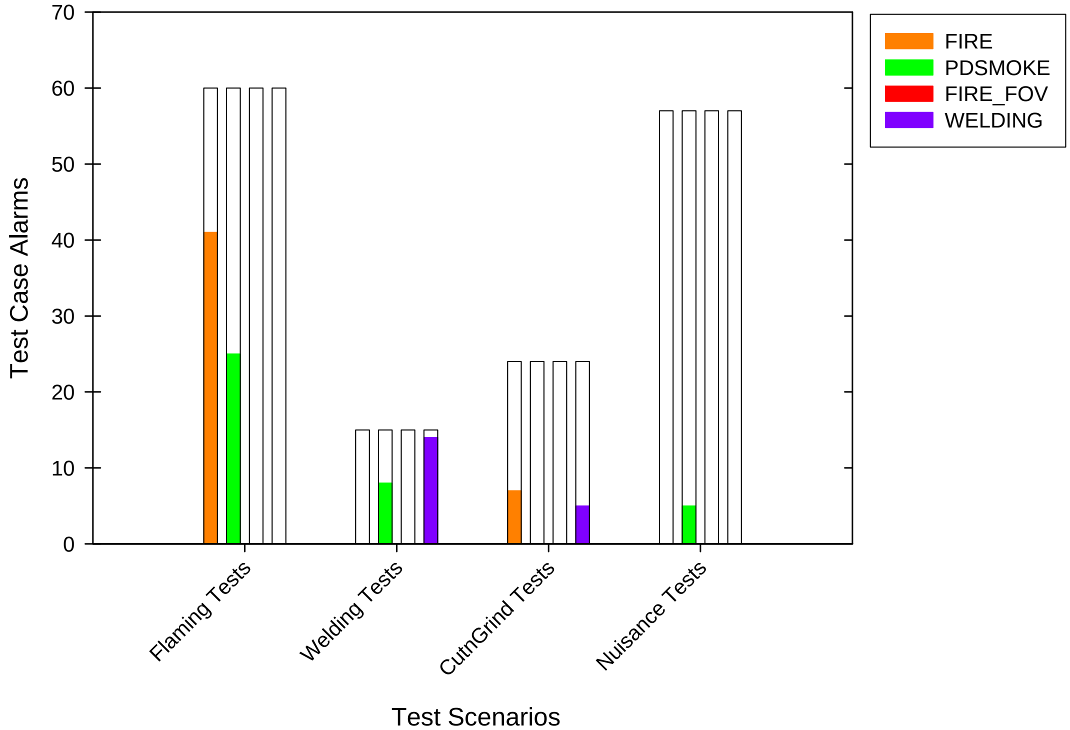

Figure 5-4 – SBVS Component Prototype 'As-Tested' algorithm results by test scenario type

In Figure 5-5, the same results as presented in Table 5-1 are shown, classified now for comparison to the overall VSP performance results. The FIRE and FIRE_FOV EVENT outputs are combined such that an alarm from either EVENT will produce a FLAME alarm. The two EVENTS are treated equally. The PDSMOKE and WELDING EVENTs directly map to the SMOKE and WELDING alarms.

To simulate an overall system response, the RESPOND alarm is a composite of the other three alarms such that if either the FLAME or SMOKE alarms are generated and the WELDING alarm is not active, a RESPOND alarm is generated. For the VS4 SBVS Component Prototype, the RESPOND results are given for the four test scenario classes in Table 5-2.

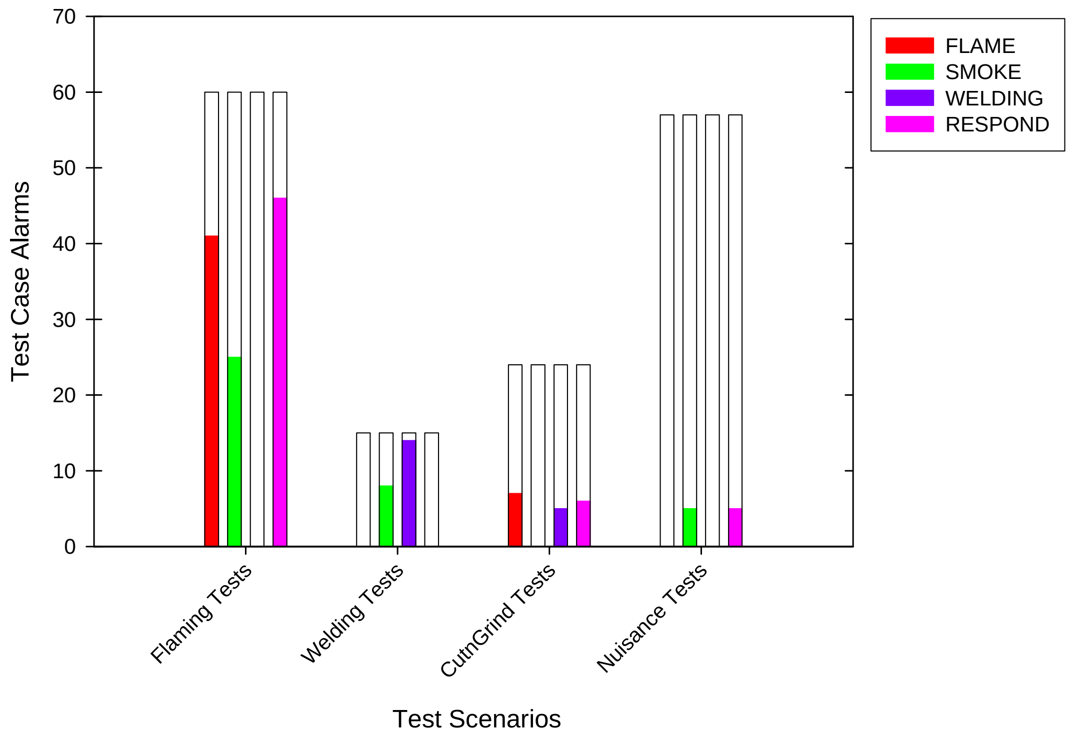

Figure 5-5 – SBVS Component Prototype ‘As-Tested’ response results by test scenario class

Table 5-2 – SBVS Component Prototype ‘As-Tested’ response results by test scenario class

Actual VS4 Performance	**FLAME**	**SMOKE**	**WELDING**	**RESPOND**
Flaming Tests	41	25	0	46
Welding Tests	0	8	14	0
Cutting and Grinding Tests	7	0	5	6
Nuisance Tests	0	5	0	5

For comparison, the VS4 As-Tested response results for both VSPs are given. Each VSP used the same SBVS, LWVD, and acoustics (ACST) data streams and one of the VIDS data streams: either the Fastcom SFA (FM1) or axonX Signifire (FM2). The FM1 and FM2 response results are given in Figure 5-6 and Figure 5-7, respectively, and in Table 5-3 and Table 5-4, respectively. For both VSPs, the overall system demonstrated superior detection results as compared to the SBVS Component Prototype alone, as would be expected. However, both VSPs were significantly more vulnerable to false alarms from the nuisance tests than the SBVS Component Prototype alone.

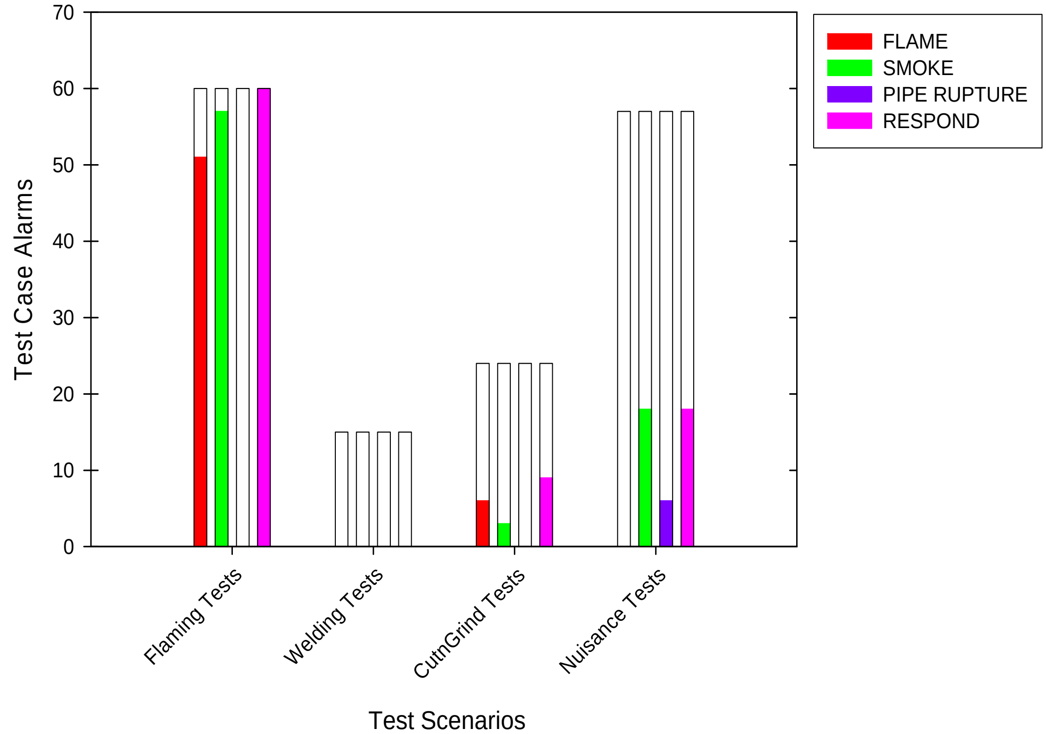

Figure 5-6 – VSP FM1 response results by test scenario class

Table 5-3 – VSP FM1 response results by test scenario class

FM1 - Fastcom	Flame	Smoke	Pipe Rupture	Respond
Flaming Tests	51	57	0	60
Welding Tests	0	0	0	0
Cutting and Grinding Tests	6	3	0	9
Nuisance Tests	0	18	6	18

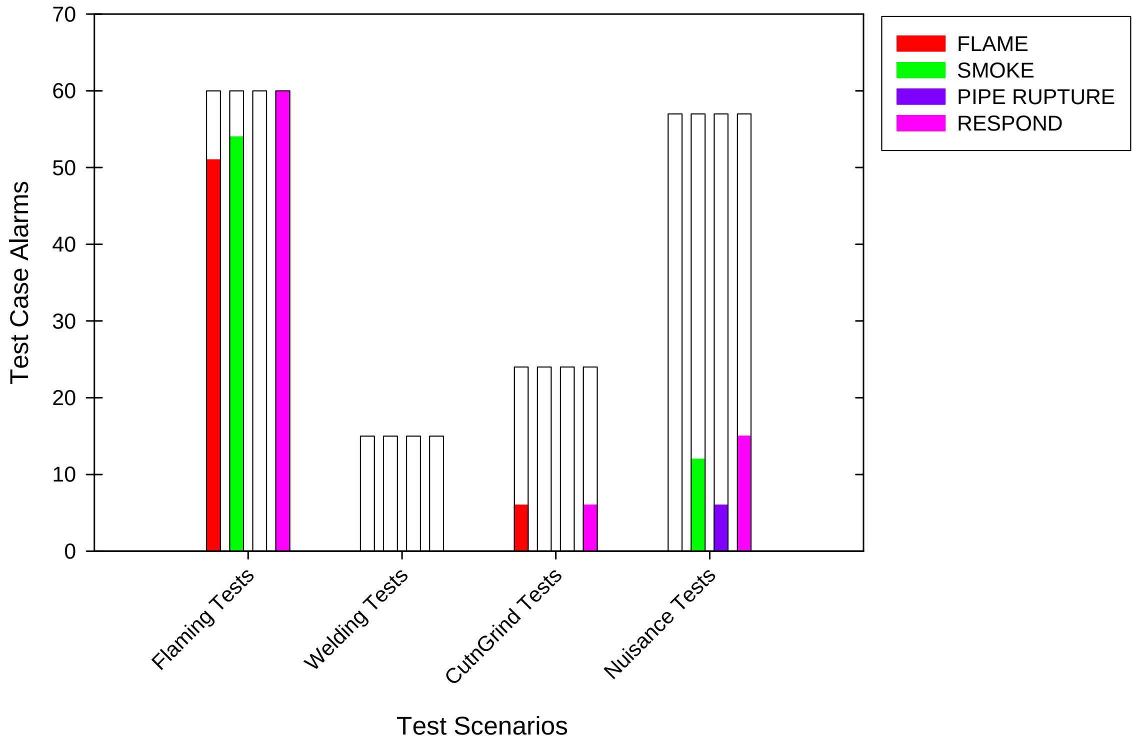

Figure 5-7 – VSP FM2 response results by test scenario class

Table 5-4 – VSP FM2 response results by test scenario class

FM2 - axonX	Flame	Smoke	Pipe Rupture	Respond
Flaming Tests	51	54	0	60
Welding Tests	0	0	0	0
Cutting and Grinding Tests	6	0	0	6
Nuisance Tests	0	12	6	15

5.3.2. INITIAL OPTIMIZATION (2005)

An initial assessment of the potential for down-selecting SBVS sensor elements for inclusion in the AiOVS mock-up was conducted in 2005 prior to the construction of the AiOVS mock-up by VMI. A two-element configuration was selected using the UV and IR sensor elements from the SBVS Component Prototype. The results are shown in Figure 5-8 and Figure 5-9 and Table 5-5 and Table 5-6. The FIRE EVENT correctly detected 48 of the 60 flaming test scenarios with only 4 false alarms. One false alarm was a special welding test scenario (VS4-08) where a high-power welder was used. This test scenario was not repeated. The remaining three false alarms were from the nuisance test scenarios and from ‘hot work’ nuisances such as heat guns and space heaters (VS4-34, -98, and -100). In each of the four test cases, only one of the three SBVS Component Prototypes in the space alarmed. This allows for potential suppression of the false alarm, if appropriate, at the data fusion level of the VSP using compartment-level situational awareness. For the FIRE_FOV EVENT, optimization led to detections in 14 of the 60 flaming test scenarios with no false alarms in the other classes. The FIRE_FOV algorithm is designed to be an indication of a larger fire than might be detected by the FIRE EVENT, so it is not possible to know *a* *priori* what the correct value should be with the data available. The WELDING EVENT was optimized and had a P_d of 1.00 for the welding test scenario class with 5 false alarms in the cutting and grinding test scenario class. Based on these analyses, the two-component configuration was suggested for the AiOVS mock-up. The PDSMOKE columns are grayed out to reflect the fact that without the Na PD data stream, the PDSMOKE EVENT cannot generate an EVENT.

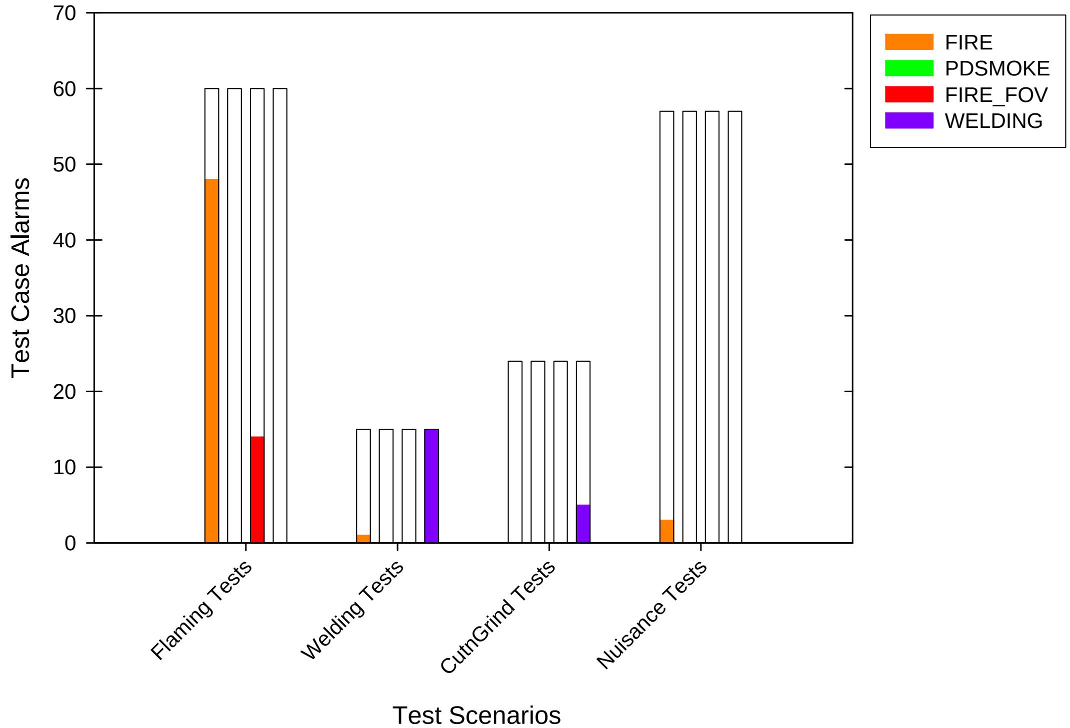

Figure 5-8 – SBVS Component Prototype 2005 UV/IR configuration algorithm results by test scenario class

Table 5-5 – SBVS Component Prototype 2005 UV/IR configuration algorithm results by test scenario class

	FIRE	PDSMOKE	FIRE_FOV	WELDING
Flaming	48 / 60	0 / 60	14 / 60	0 / 60
Welding	1 / 15	0 / 15	0 / 15	15 / 15
Cutting and Grinding	0 / 24	0 / 24	0 / 24	5 / 24
Nuisances	3 / 57	0 / 57	0 / 57	0 / 57

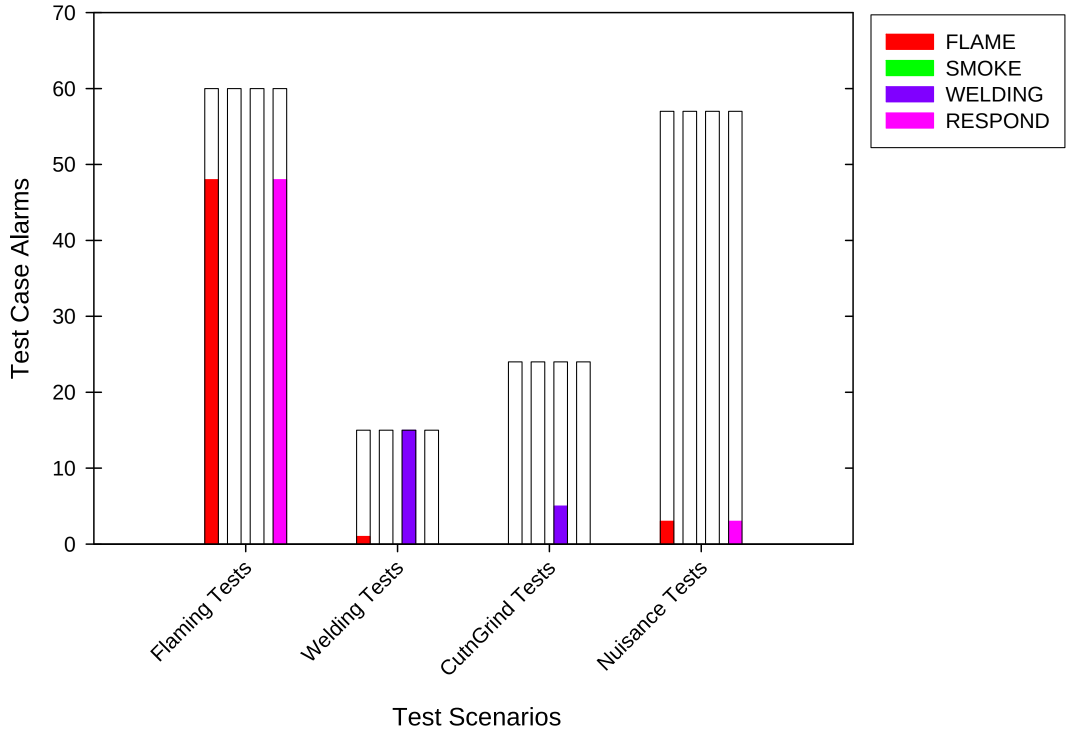

Figure 5-9 – SBVS Component Prototype 2005 UV/IR configuration response results by test scenario class

Table 5-6 – SBVS Component Prototype 2005 UV/IR configuration response results by test scenario class

Initial Optimization - UV / MIR Only	FLAME	SMOKE	WELDING	RESPOND
Flaming Tests	48	0	0	48
Welding Tests	1	0	15	0
Cutting and Grinding Tests	0	0	5	0
Nuisance Tests	3	0	0	3

5.3.3. FATE OF THE PDSMOKE EVENT

Only the PDSMOKE EVENT incorporates the 5900 Å data stream (other than the generic EVENT EVENT) in the SBVS Component Prototype. The main focus of the SBVS Component Prototype has always been on flaming sources, to which the VIDS are not very sensitive. Therefore, it was determined that the modest performance of the PDSMOKE EVENT, as compared to the VIDS, shown in the previous section is not worth the additional cost of retaining the Na PD in the AiOVS. The 5900 Å data stream was not considered further in this analysis. As the PDSMOKE EVENT is decoupled from the other EVENTs, it would be a fairly straight forward activity to restore and optimize the PDSMOKE capability at a later date, if so desired.

5.3.4. FIRE AND FIRE_FOV EVENTS

A focused reprocessing and analysis of the performance of the FIRE and FIRE_FOV EVENTs was undertaken. The VS4 As-Tested results show that the measured performance of these EVENTs was not acceptable, with no FIRE_FOV EVENT detections and detection of only 41 of 60 flaming test scenarios by the FIRE EVENT. Additionally, improvement of the false alarm rate for the FIRE EVENT (7 of 96) was desirable. Each available parameter of each EVENT was systematically varied and evaluated using a threshold curve. An example is shown in Figure 5-10. The context of the example will be explained later in this section. In this example, the FIRE EVENT for a particular sensor configuration is being evaluated. The probability of detection (P_d, the fraction of flaming test scenarios correctly classified), the probability of correct classification (P_{corr}, the fraction of flaming test scenarios correctly classified as FIRE and the number of non-flaming test scenarios not classified as FIRE), and the probability of false alarm (P_{fa}, the fraction of non-flaming test scenarios incorrectly classified as FIRE) are plotted as a function of the FIRE EVENT SumN threshold value. The blue vertical line indicates both the initial stating point and the optimal operating point, which are the same in this case. Increased SumN threshold leads to a reduced P_d while decreased SumN threshold leads to an increase in P_{fa} (and corresponding decrease in P_{corr}).

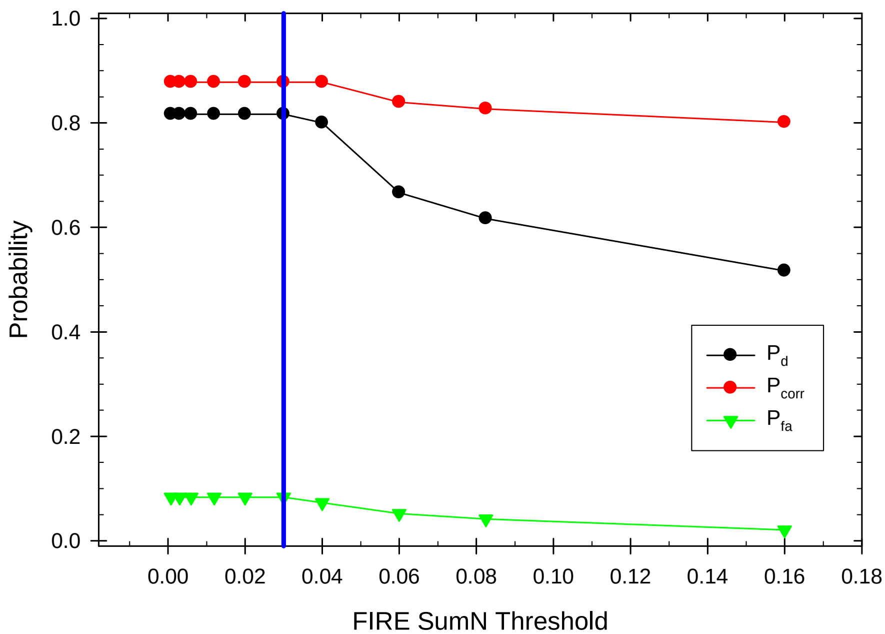

Figure 5-10 – Example threshold curve for the optimization of the FIRE EVENT SumN threshold for the K/UV/IR 3-element combination

Using this analysis scheme, four different potential configurations for the SBVS portion of the AiOVS were studied and their performance results for the same data set were determined. Four potential data streams are available, the 7665 Å Si PD (K), the 10500 Å Si PD (NIR), the UV gas discharge tube (UV), and the 4.3 µm IR (IR) detector. The four configurations are: a) UV/IR, b) K/UV/IR, c) NIR/UV/IR, and d) K/NIR/UV/IR. The evaluation of each EVENT (the FIRE and FIRE_FOV EVENTs, and the WELDING EVENT in the next section) for a data point is made independently. This allows the performance of each EVENT to be optimized independently.

The results for the four configurations are given in Table 5-7 through Table 5-16 and Figure 5-11 through Figure 5-20. In the case of the 4-element configuration, results for two different SumN thresholds for the FIRE EVENT are presented as a balance between P_d and P_{fa} considerations.

Table 5-7 – UV/IR configuration algorithm results

	FIRE	PDSMOKE	FIRE_FOV	WELDING
Flaming	48 / 60	0 / 60	18 / 60	0 / 60
Welding	1 / 15	0 / 15	0 / 15	15 / 15
Cutting and Grinding	0 / 24	0 / 24	0 / 24	0 / 24
Nuisances	3 / 57	0 / 57	0 / 57	0 / 57

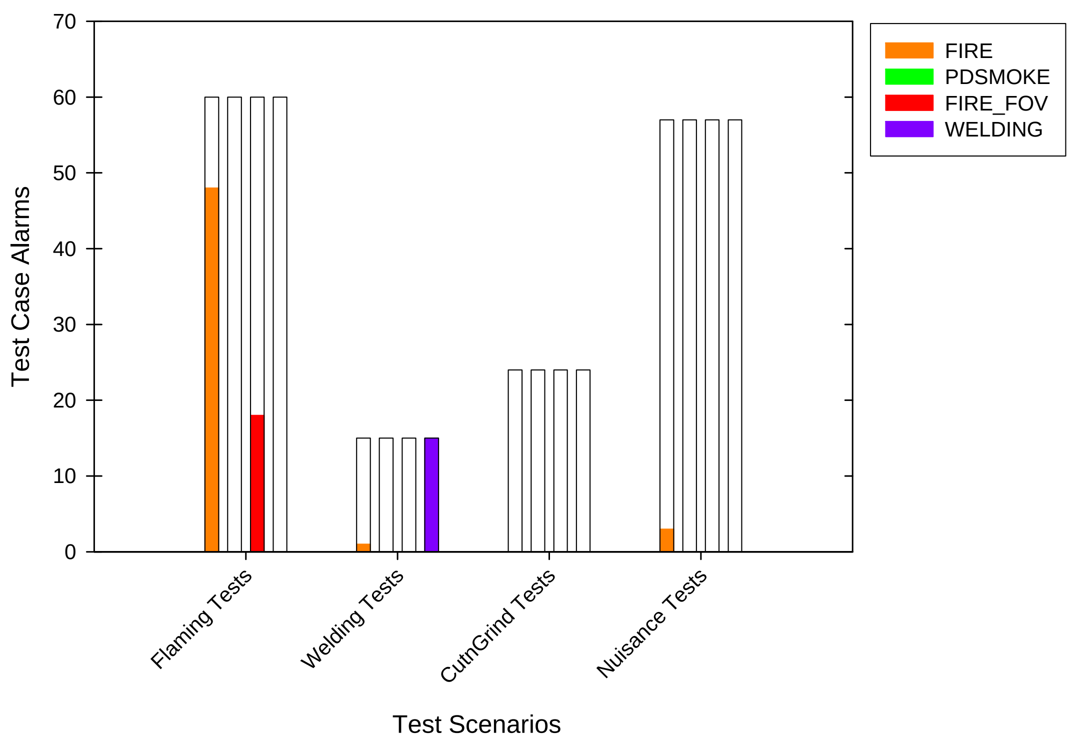

Figure 5-11 – UV/IR configuration algorithm results by test scenario type

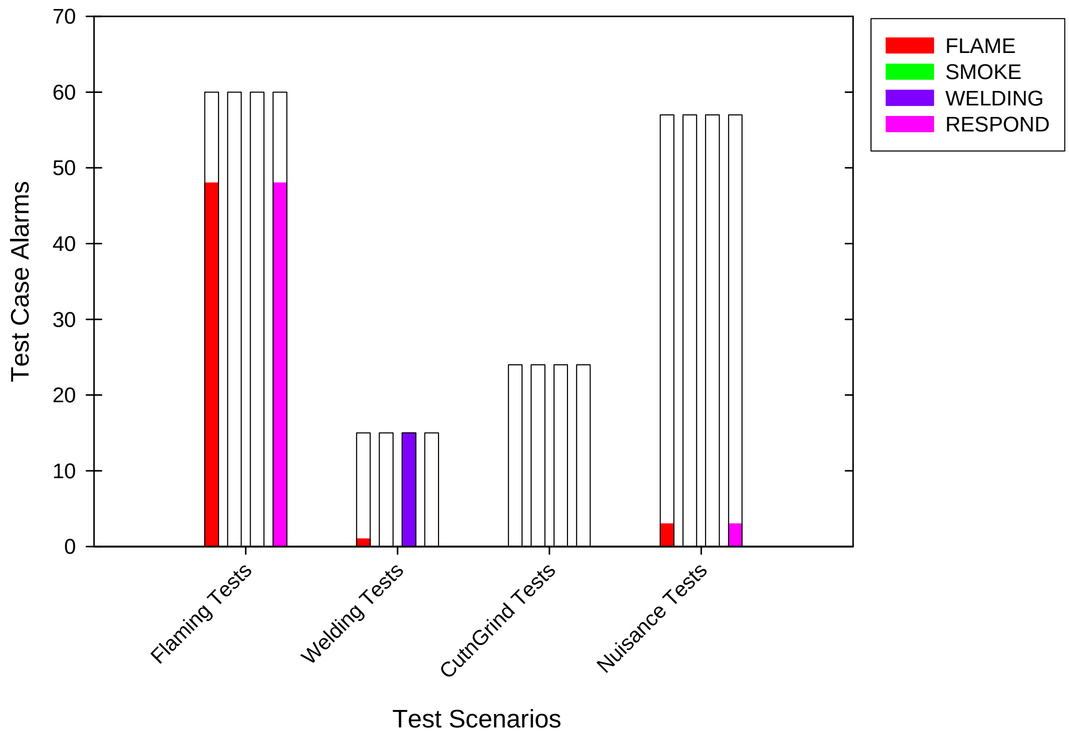

Figure 5-12 – UV/IR configuration response results by test scenario class

Table 5-8 – UV/IR configuration response results by test scenario class

New UV/MIR Optimization	FLAME	SMOKE	WELDING	RESPOND
Flaming Tests	48	0	0	48
Welding Tests	1	0	15	0
Cutting and Grinding Tests	0	0	0	0
Nuisance Tests	3	0	0	3

Table 5-9 – K/UV/IR configuration algorithm results

	FIRE	PDSMOKE	FIRE_FOV	WELDING
Flaming	49 / 60	0 / 60	18 / 60	0 / 60
Welding	0 / 15	0 / 15	0 / 15	15 / 15
Cutting and Grinding	8 / 24	0 / 24	0 / 24	0 / 24
Nuisances	0 / 57	0 / 57	0 / 57	0 / 57

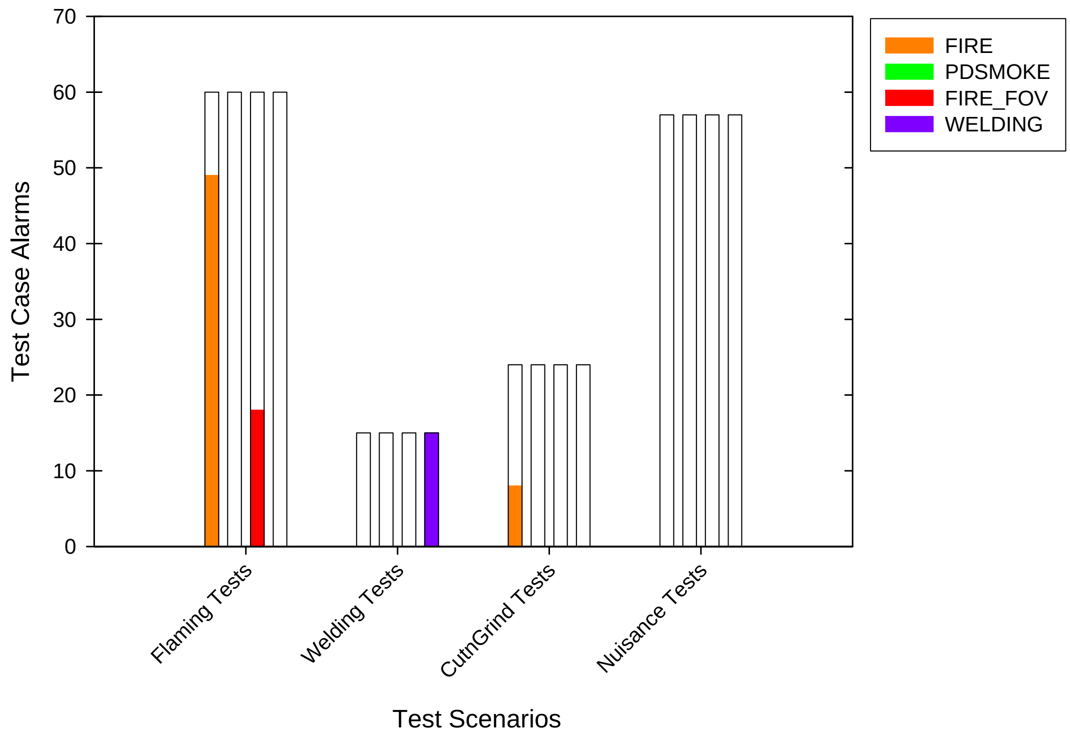

Figure 5-13 – K/UV/IR configuration algorithm results by test scenario type

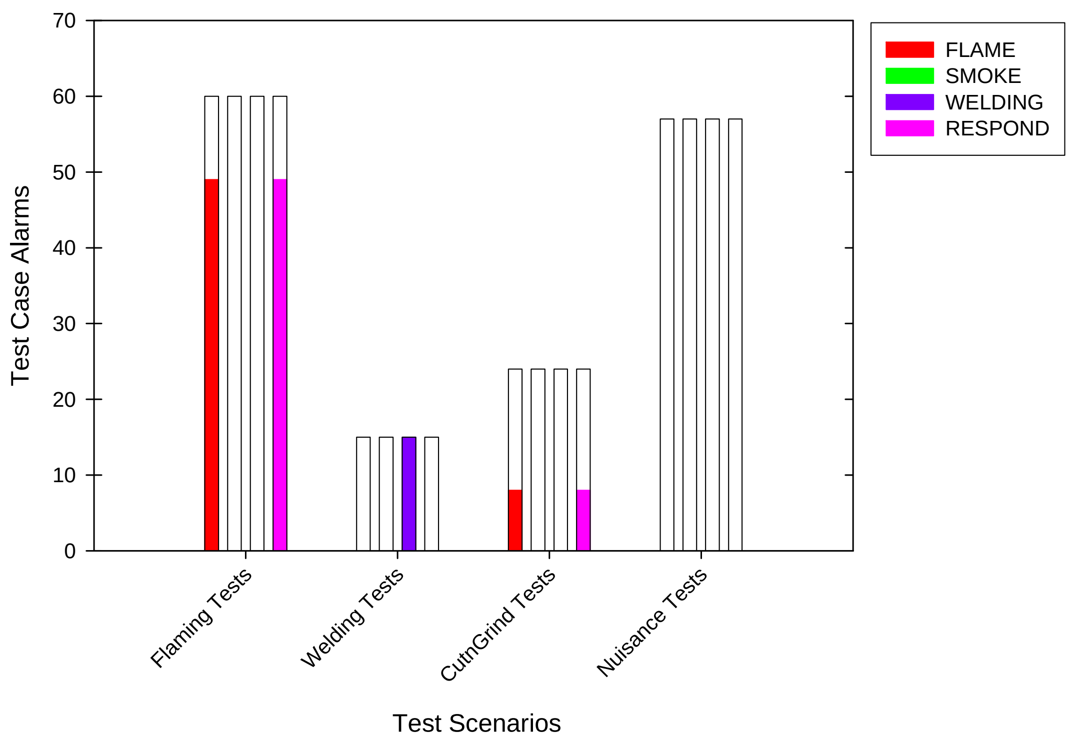

Figure 5-14 – K/UV/IR configuration response results by test scenario class

Table 5-10 – K/UV/IR configuration response results by test scenario class

New Opt. - K, MIR, UV	FLAME	SMOKE	WELDING	RESPOND
Flaming Tests	49	0	0	49
Welding Tests	0	0	15	0
Cutting and Grinding Tests	8	0	0	8
Nuisance Tests	0	0	0	0

Table 5-11 – NIR/UV/IR configuration algorithm results

	FIRE	PDSMOKE	FIRE_FOV	WELDING
Flaming	57 / 60	0 / 60	18 / 60	0 / 60
Welding	0 / 15	0 / 15	0 / 15	15 / 15
Cutting and Grinding	9 / 24	0 / 24	0 / 24	0 / 24
Nuisances	0 / 57	0 / 57	0 / 57	0 / 57

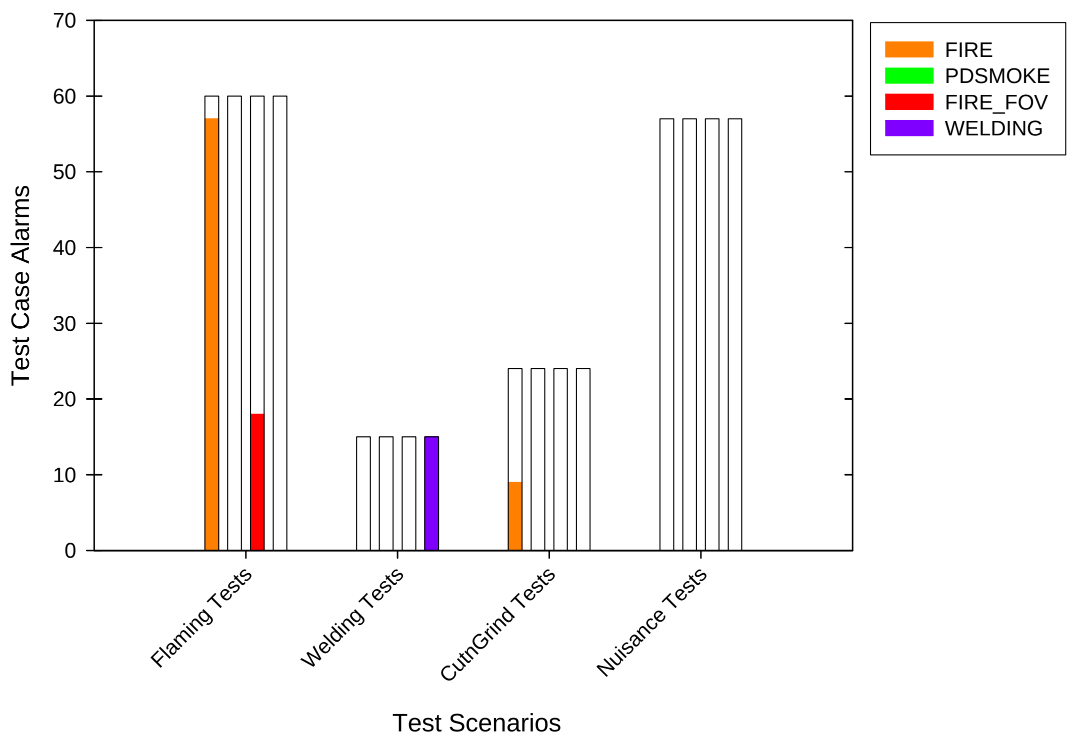

Figure 5-15 – NIR/UV/IR configuration algorithm results by test scenario type

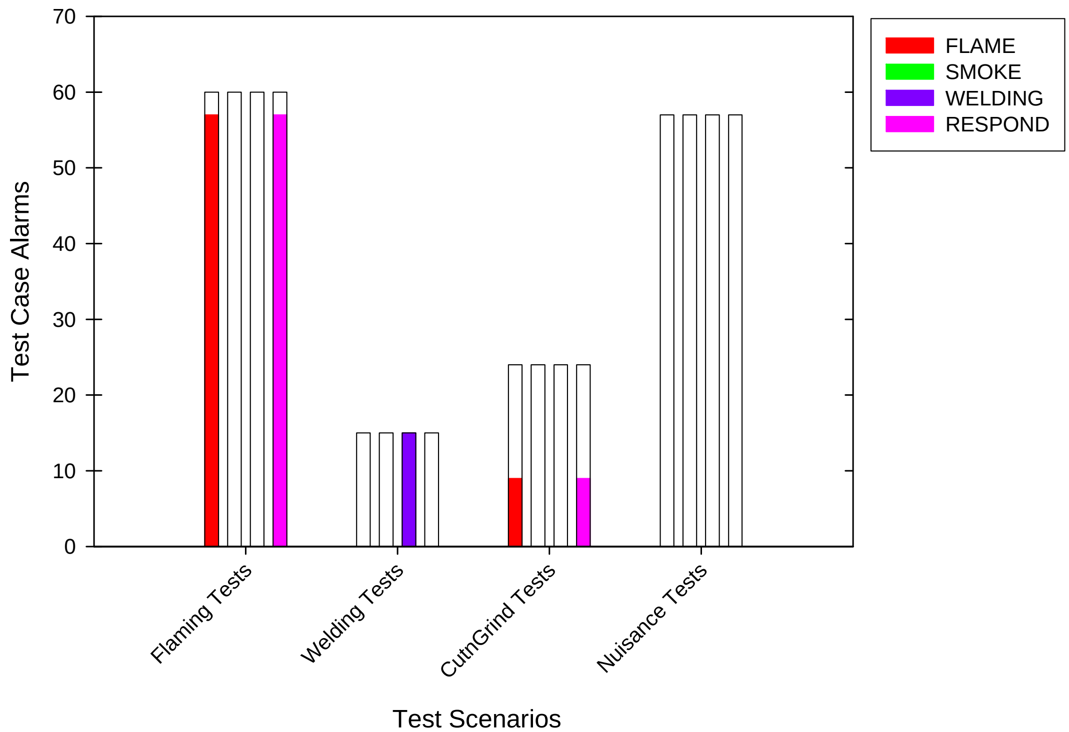

Figure 5-16 – NIR/UV/IR configuration response results by test scenario class

Table 5-12 – NIR/UV/IR configuration response results by test scenario class

New Opt. - NIR, MIR, UV	FLAME	SMOKE	WELDING	RESPOND
Flaming Tests	57	0	0	57
Welding Tests	0	0	15	0
Cutting and Grinding Tests	9	0	0	9
Nuisance Tests	0	0	0	0

Table 5-13 – K/NIR/UV/IR, Small SumN configuration algorithm results

	FIRE	PDSMOKE	FIRE_FOV	WELDING
Flaming	59 / 60	0 / 60	18 / 60	0 / 60
Welding	0 / 15	0 / 15	0 / 15	15 / 15
Cutting and Grinding	10 / 24	0 / 24	0 / 24	0 / 24
Nuisances	1 / 57	0 / 57	0 / 57	0 / 57

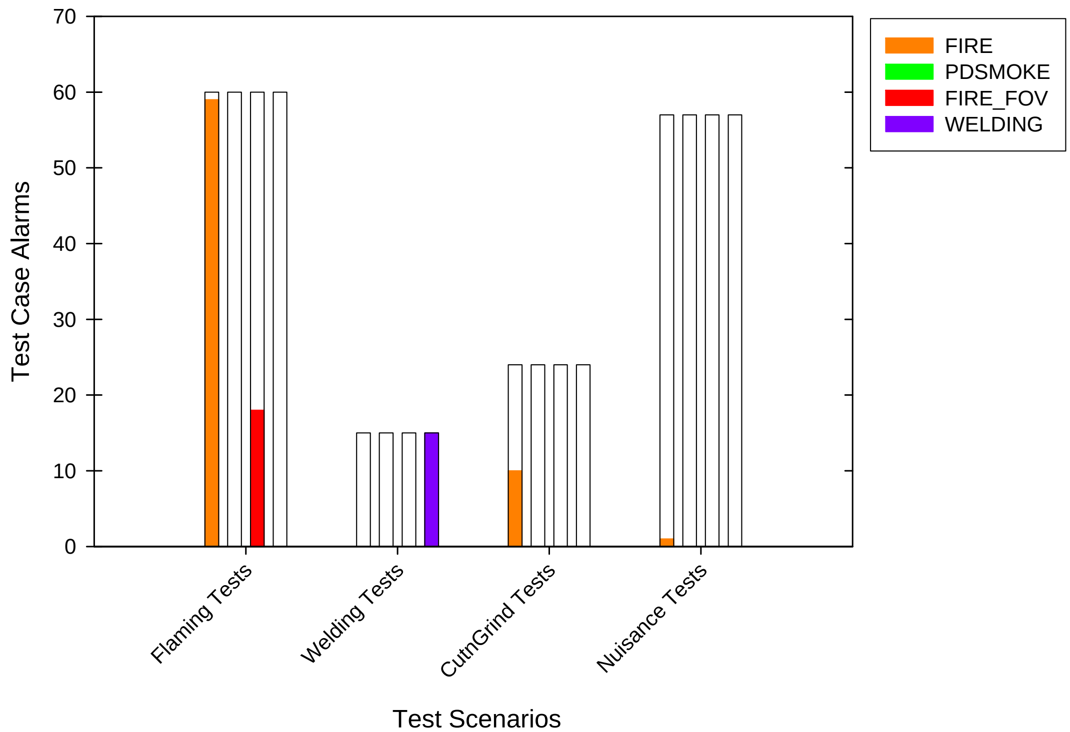

Figure 5-17 – K/NIR/UV/IR, Small SumN algorithm results by test scenario type

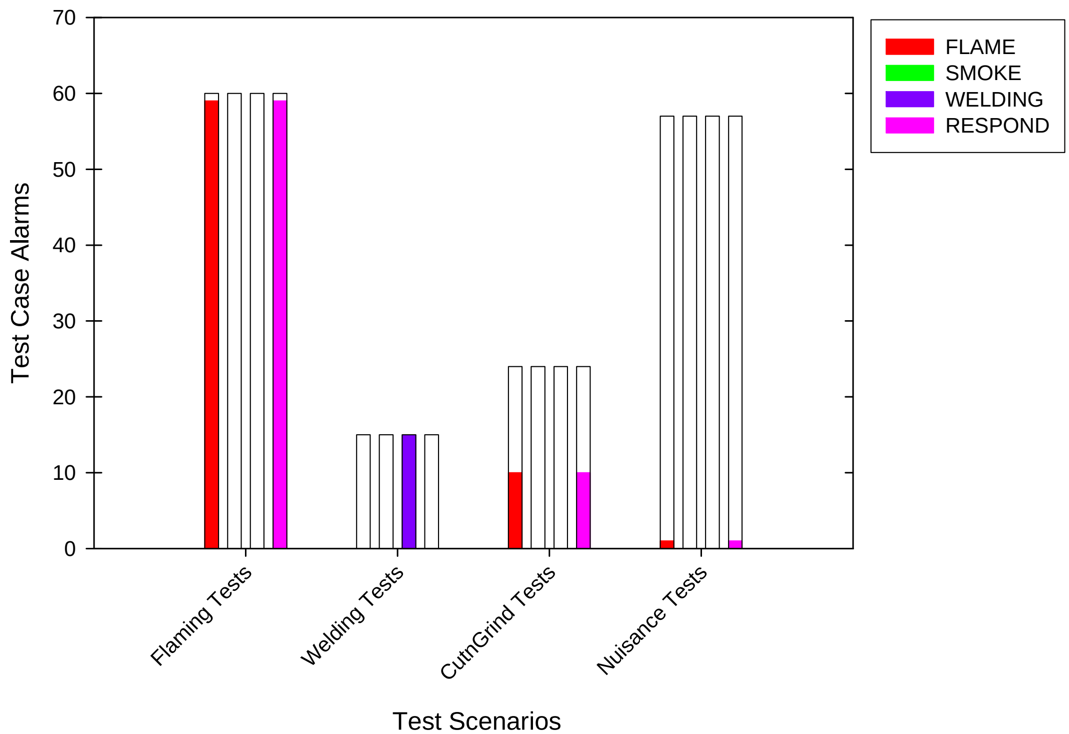

Figure 5-18 – K/NIR/UV/IR, Small SumN response results by test scenario class

Table 5-14 – K/NIR/UV/IR, Small SumN response results by test scenario class

New Opt. 4 Element - Small SumN	FLAME	SMOKE	WELDING	RESPOND
Flaming Tests	59	0	0	59
Welding Tests	0	0	15	0
Cutting and Grinding Tests	10	0	0	10
Nuisance Tests	1	0	0	1

Table 5-15 – K/NIR/UV/IR, Large SumN algorithm results

	FIRE	PDSMOKE	FIRE_FOV	WELDING
Flaming	58 / 60	0 / 60	18 / 60	0 / 60
Welding	0 / 15	0 / 15	0 / 15	15 / 15
Cutting and Grinding	9 / 24	0 / 24	0 / 24	0 / 24
Nuisances	0 / 57	0 / 57	0 / 57	0 / 57

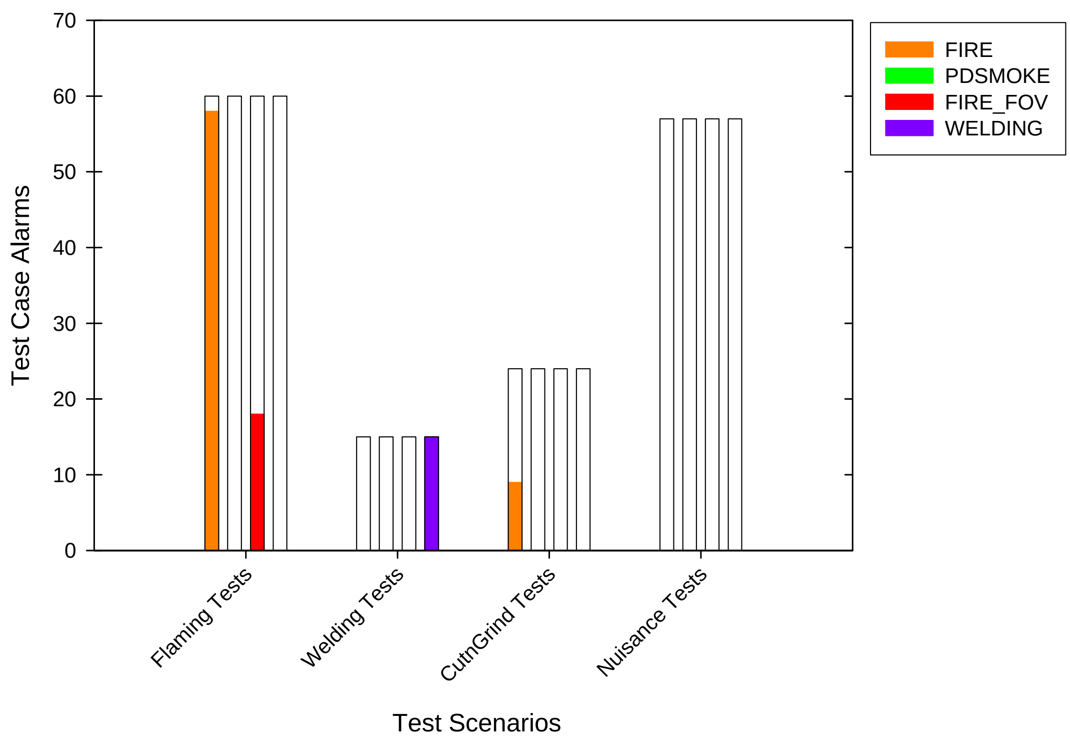

Figure 5-19 – K/NIR/UV/IR, Large SumN algorithm results by test scenario type

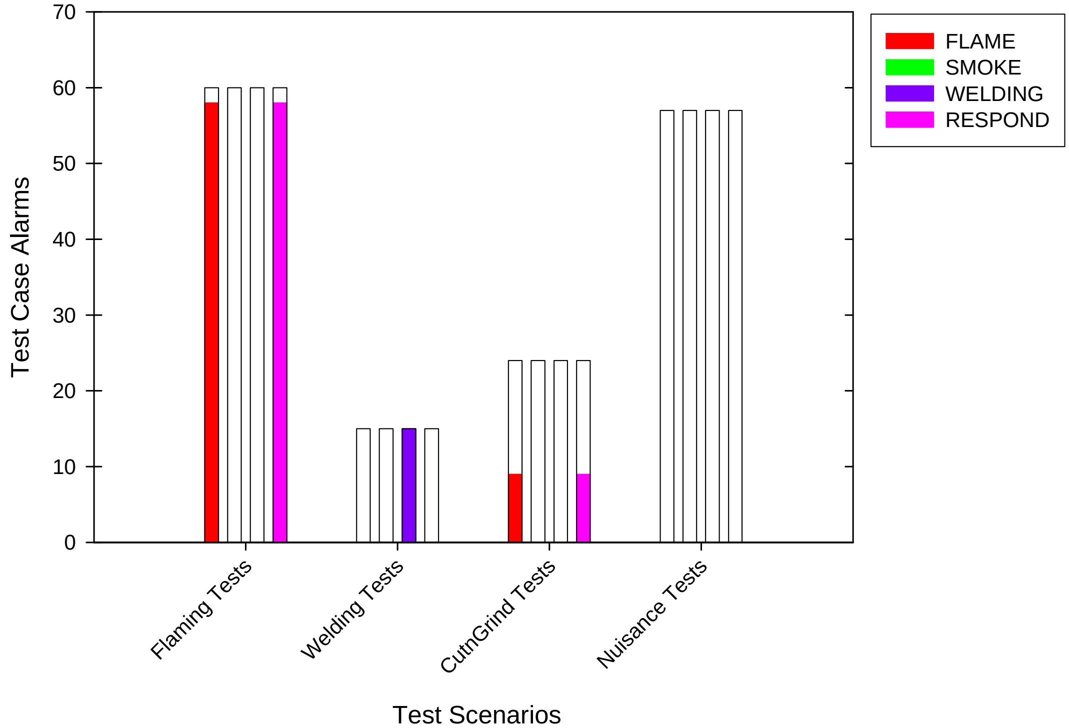

Figure 5-20 – K/NIR/UV/IR, Large SumN response results by test scenario class

Table 5-16 – K/NIR/UV/IR, Large SumN response results by test scenario class

New Opt. 4 Element Large SumN	FLAME	SMOKE	WELDING	RESPOND
Flaming Tests	58	0	0	58
Welding Tests	0	0	15	0
Cutting and Grinding Tests	9	0	0	9
Nuisance Tests	0	0	0	0

5.3.5. WELDING EVENTS

Review of any of the optimizations in the previous section shows that it is possible to achieve a P_d of 100% for welding test scenarios with a P_{fa} of 0%. The VSP data fusion algorithms [11] rely heavily on the SBVS WELDING EVENT to guard against false alarms generated by the other components, including the other SBVS EVENTs.

6. RESULTS AND RECOMMENDATIONS

As discussed in Section 5, it is possible to retrospectively achieve better performance for the VS4 data subset used in this report than was originally demonstrated during the live demonstration. Additionally, it is possible to recover better performance retrospectively with fewer sensor elements than was achieved during the original demonstration.

The new optimization of the UV/IR configuration shows improved performance over the as-tested configuration and the original 2005 optimization. The P_d of the FIRE EVENT was improved from 0.68 to 0.80 through optimization, while reducing the number of false positives from 7 to 4. The P_d of the WELDING EVENT was also improved from 0.93 to 1.00 through optimization. The FIRE_FOV EVENT, which did not alarm for any of the selected test scenarios during the live demonstration and alarmed for 14 of the 60 test scenarios in the 2005 optimization, was further improved to 18 out of 60 detections. As can be seen from Figure 5-10, the features in the algorithm parameter space are not sharp features and the algorithm parameter thresholds are not placed in regions of rapid change. This makes the response of the algorithms relatively stable with respect to issues such as inter-sensor calibration. As an example, consider the discussion in the previous section regarding the two possible 4-element configurations. Increasing the threshold value for a key parameter, SumN, by 41% (from 0.17 to 0.24) changes the P_d for the FIRE EVENT from 0.98 to 0.95 and the P_{fa} from 0.09 to 0.11.

Adding additional sensor elements to the configuration leads to increased P_d for the FIRE EVENT as shown in Figure 6-1 with increasing P_{fa} (see Section 5.3). The K/UV/IR combination offers little improvement in the FIRE Event P_d (0.82 vs. 0.80) while doubling the number of false alarms. This combination is not recommended. The NIR/UV/IR combination offers significant improvement in the FIRE EVENT P_d (0.95 vs. 0.80) while only adding 5 additional false alarms over the UV/IR combination. Especially interesting is that the FIRE EVENT false alarms generated are moved from the nuisance and welding test scenario classes to the cutting and grinding class. Hot work of these types is not typically conducted without significant preparation and system-wide notification in a shipboard environment and any DCA systems would most likely be secured or operating in a special mode to handle this type of work. This reduces the potential severity of the generated false alarms. Using all four elements achieves an almost perfect P_d for the FIRE EVENT (0.98 or 0.97 vs 0.80) while adding only 5-7 additional false alarms, depending on the threshold setting for the SumN parameter. In the case of the smaller SumN threshold, one of the new false alarms is from the nuisance test scenario class while all others are from the cutting and grinding test scenario class. There are trade-offs between sensitivity and selectivity. From the data fusion perspective, data from other sources can be used to tailor overall system performance.

An example of where inter-component data fusion might successfully be used in the VSP is with the LWVD Component, which takes a long-pass filtered black and white video image and generates a single luminosity value for the image. The long-pass filter's design cut-off wavelength is 720 nm which is closely matched to center wavelength of the interference filter on the NIR PD sensor element. One could potentially use the LWVD luminosity data stream in lieu of the NIR PD data stream to produce an effective 3-component SBVS system with only the UV and IR sensor elements. Or an effective 4-component system could be produced with only the K, UV, and IR sensor elements. This would require that the LWVD data stream have similar sensitivity and dynamic range to that of the photodiode. Testing along these lines is currently ongoing.

On the basis of these analyses, the current recommendation for the SBVS Component in the AiOVS being developed by VMI is either a UV/IR or a NIR/UV/IR configuration, depending on the data fusion systems' tolerance for increased P_{fa} with increased P_d. The EVENT parameters for the four potential configurations discussed here are given in Appendix C.

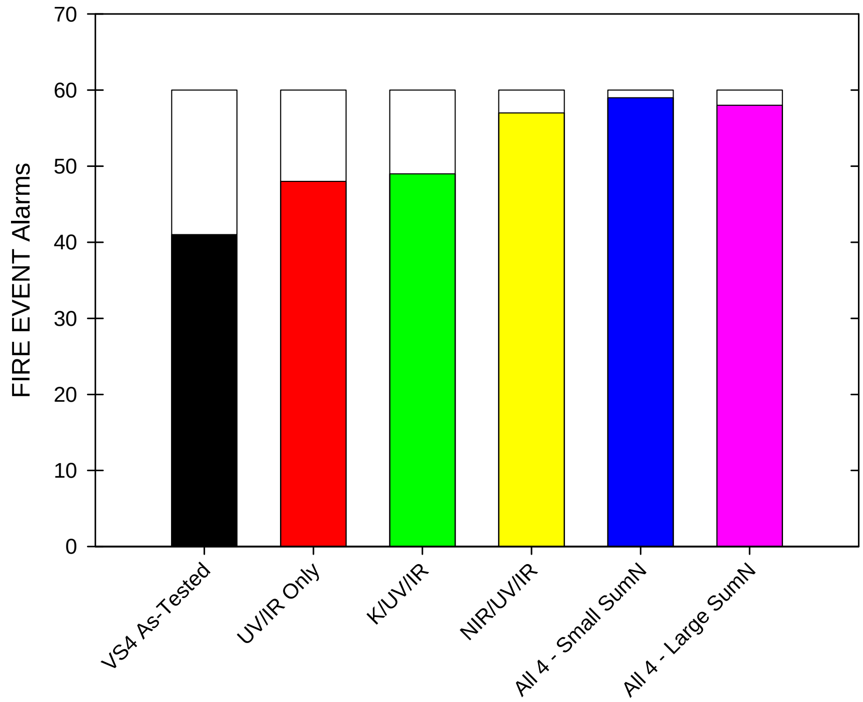

Figure 6-1 – Flaming test scenario results for the FIRE EVENT for the potential SBVS configurations discussed in the text. The outline bars indicate the maximum number of alarms possible (60).

7. REFERENCES

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APPENDIX A. SBVS EVENT ALGORITHM DEFINITIONS AND PARAMETERS

The finalized SBVS EVENT criteria and parameters as used in the VS5 and DD(X) Test Series were:

```
Event:      If (Sum_N >= 0.0825) or (Abs(5900A) >= 0.015) Then
                  EVENT = TRUE
            Else
                  EVENT = FALSE.

Smoke:      If Abs(5900A) >= 0.043 Then
                  PDSMOKE = TRUE
            Else
                  PDSMOKE = FALSE.

Fire:       IF (Sum_N >= 0.0825) and (7665A >= 0.015) and
            (10500A >= 0.015) and (RefIR/UV >= 1) Then
                  FIRE = TRUE
            Else
                  FIRE = FALSE.

Fire_FOV:   IF (Sum_N >= 0.6) and (7665A >= 0.015) and
            (10500A >= 0.015) and (RefIR >= 0.2) and (UV >= 0.001) Then
                  FIRE_FOV = TRUE
            Else
                  FIRE_FOV = FALSE.

Welding:    IF (Sum_N >= 0.0825) and (7665A >= 0.015) and (10500A >= 0.015)
            and (RefIR < 0.056) and (UV >= 0.175) Then
                  WELDING = TRUE
            Else
                  WELDING = FALSE.

Persistence:
      IF EVENT_TYPE = TRUE
                  EVENT_TYPE.IndexCount = EVENT_TYPE.IndexCount + 1
                  IF EVENT_TYPE.IndexCount > 5[1]
                        EVENT_TYPE.IndexCount = 5[1]
      ELSE
                  EVENT_TYPE.IndexCount = EVENT_TYPE.IndexCount – 1
                  IF EVENT_TYPE.IndexCount < 0
                        EVENT_TYPE.IndexCount = 0
      IF EVENT_TYPE.IndexCount >= Persistence[1]
                  EVENT_TYPE.ALARM = TRUE
      ELSE
                  EVENT_TYPE.ALARM = FALSE.
```

[1] For the PDSMOKE EVENT, the persistence value is 25 seconds, not 5.

APPENDIX B. SBVS SENSOR SUITE SCALE FACTORS

Each of the nine SBVS Component Prototype sensor suites and the AiOVS mock-up have individual scale factors for calibration and inter-unit uniformity in response. The factors for the existing units are listed below in Table B-1. There are four generations of units: the original units (S/N 51 – 53), the second generation (S/N 54 and 55), the third generation (S/N 56 – 59), and the AiOVS mockup (S/N 21). The RefIR1 scale factors for units S/N 51, 52, and 53 were updated for the DD(X) Test Series conducted during January, 2005 on the ex-USS *Shadwell*.

Table B-1 – SBVS sensor suite scale factors by unit serial number (S/N)

Unit S/N	51	52	53[a]
Unit Type	VSP	VSP	VSP
NaPD	0.2857	0.2844	0.2418
KPD	0.0471	0.0400	0.0464
NIRPD	0.1697	0.0400	0.3363
RefIR1	1.5800	1.1600	0.9600
RefIR2	3.2500	3.2500	3.2500
UV	255	255	255
DD(X)			
RefIR1	5.0380	3.7000	3.0710

[a] Unit S/N 53 has a split interference filter for RefIR2 (2.7 + 4.3 μm)

Unit S/N	54	55	56
Unit Type	VSP	VSP	VSP
NaPD	0.1050	0.1050	0.2600
KPD	0.0038	0.0038	0.0470
NIRPD	0.2530	0.2530	0.2530
RefIR1	2.1000	2.1000	0.5250
RefIR2	3.2500	3.2500	3.2500
UV	255	255	255

Unit S/N	57	58	59
Unit Type	VSP	VSP	VSP
NaPD	0.2600	0.2600	0.2600
KPD	0.0470	0.0470	0.0470
NIRPD	0.2530	0.2530	0.2530
RefIR1	0.5250	0.5250	0.5250
RefIR2	3.2500	3.2500	3.2500
UV	255	255	255

Unit S/N	21
Unit Type	AiOVS
NaPD	0.25
KPD	0.05
NIRPD	0.25
RefIR1	0.3100
RefIR2	3.2500
UV	255

APPENDIX C. SBVS EVENT PARAMETERS BY CONFIGURATION

For each of the four AiOVS configurations discussed in this report, the complete listing of SBVS algorithm parameters used in the analyses are given in Table C-1.

Table C-1 – Potential AiOVS configuration SVBS algorithm parameter values

	UV/IR	**K/UV/IR**	**NIR/UV/IR**	**K/NIR/UV/IR Small SumN**	**K/NIR/UV/IR Large SumN**
EVENT					
Sum_N	0.001	0.001	0.001	0.001	0.001
Na					
FIRE					
Sum_N	0.0017	0.0017	0.025	0.017	0.024
K		0.03		0.0007	0.0007
NIR			0.01	0.01	0.01
RefIR/UV	0.5	0.5	0.5	1	1
PDSMOKE					
Na					
FIRE_FOV					
Sum_N	0.006	0.006	0.006	0.006	0.006
K		0.015		0.015	0.015
NIR			0.015	0.015	0.015
UV	0.001	0.001	0.001	0.001	0.001
Ref_IR/UV	0.08	0.08	0.08	0.08	0.08
WELDING					
Sum_N	0.0825	0.0825	0.0825	0.0825	0.0825
K		0.015		0.015	0.015
NIR			0.01	0.01	0.01
UV	0.3	0.3	0.3	0.3	0.3
Ref_IR	0.005	0.005	0.005	0.005	0.005